WPSA Project Planning Meeting
18th March 2021

Max-Planck-Institut
für Plasmaphysik

Ideas and possibilities for

Transport modeling of electron runaway with reduced kinetic tools for JT-60SA

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HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

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EUROfusion

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Runaway electron studies in the JT-60SA Research Plan

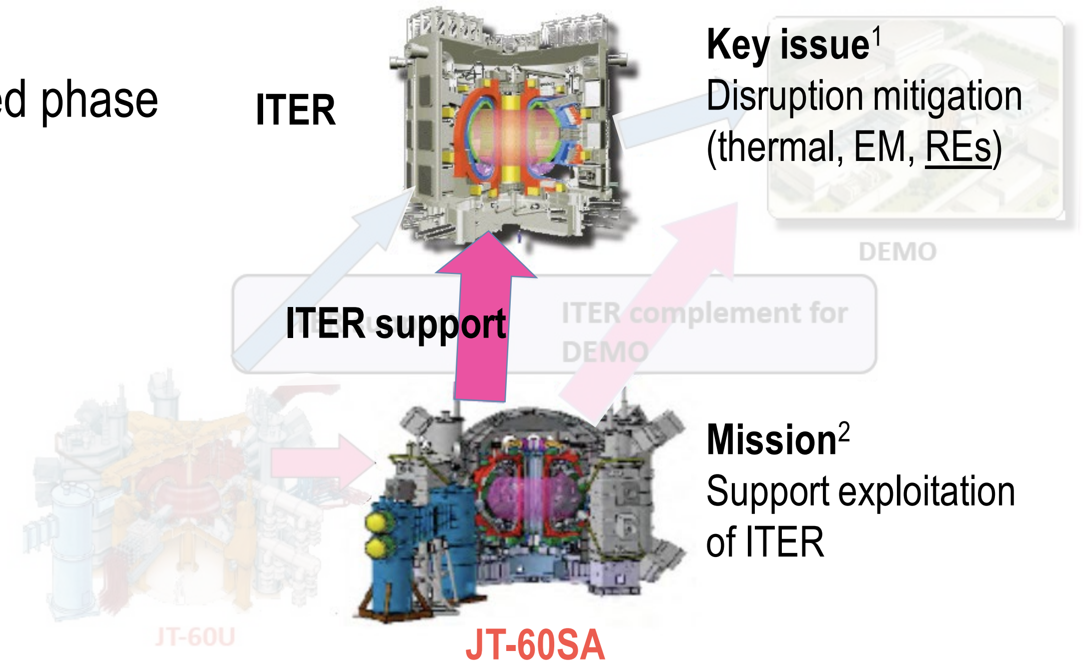
JT-60SA research strategy

Initial Research Phase I: H.I.2. ITER risk mitigation for non-activated phase

- Basic disruption studies:
  1. Estimating REs at high I_p
  2. Exp. code validation

Initial Research Phase II: H.II.3. ITER risk mitigation

- Runaway electron study at high current:
  1. Mitigation & modeling using MGI (different I_p, B_t, S)
  2. Exp. code validation
  3. Prediction of MGI for RE mitigation in ITER



Time line[2]**:** 2023 – 2024

JT-60SA	2020	2021	2022	2023	2024	2025
Initial – I (H)						
Initial – II (D)						

[1] ITER Organization. ITER Research Plan within the Staged Approach. ITR-18-003 (2018)

[2] JT-60SA Research Unit. JT-60SA Research Plan (v. 4). (2018)

The need for runaway electron modeling in JT-60SA in support of ITER

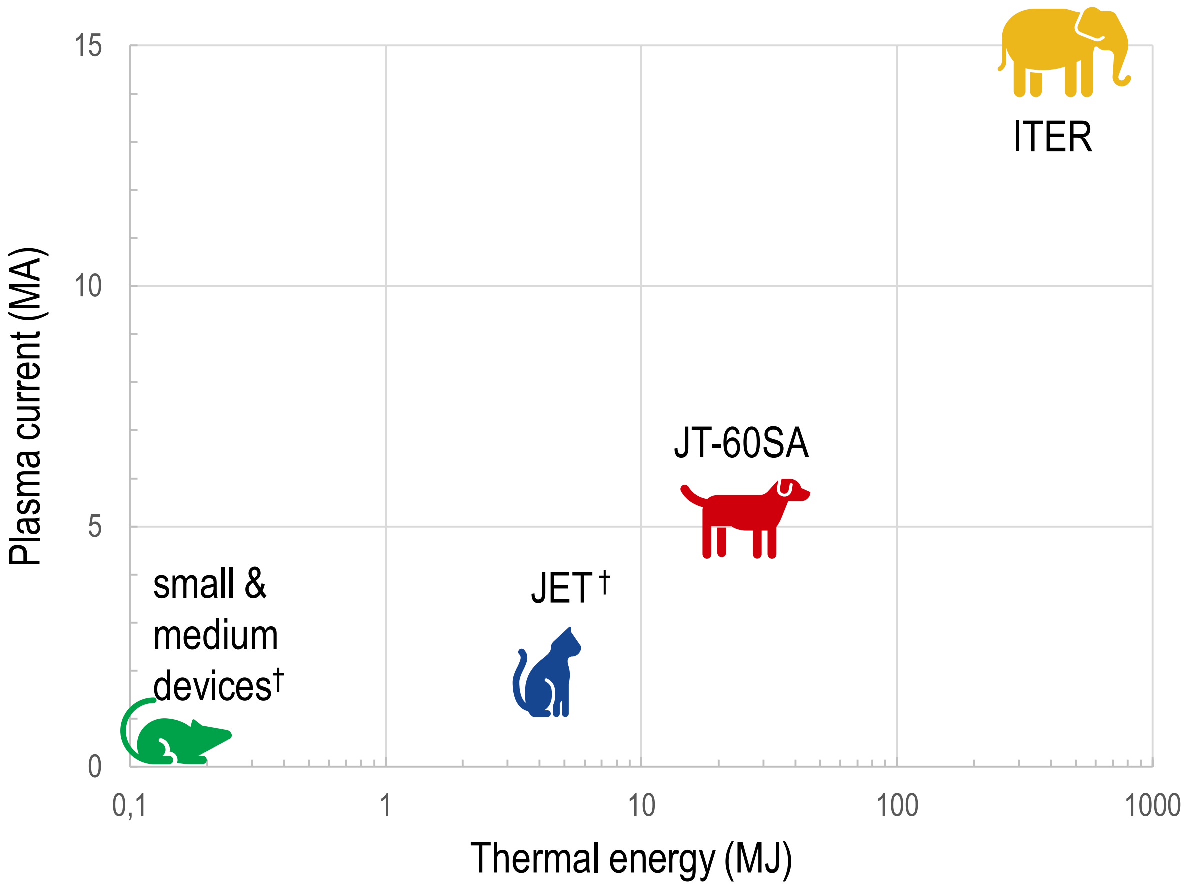
Extrapolating disruption mitigation to ITER

- Good exp. coverage of small & medium devices
- Insufficient data for large devices

→ What about ITER?

Runaway electron generation

- RE seed multiplication exponentially sensitive to available magnetic flux
- In ITER, up to 10 MA of RE current[1]
- Existing modeling tools need additional data for validation & extrapolation to ITER



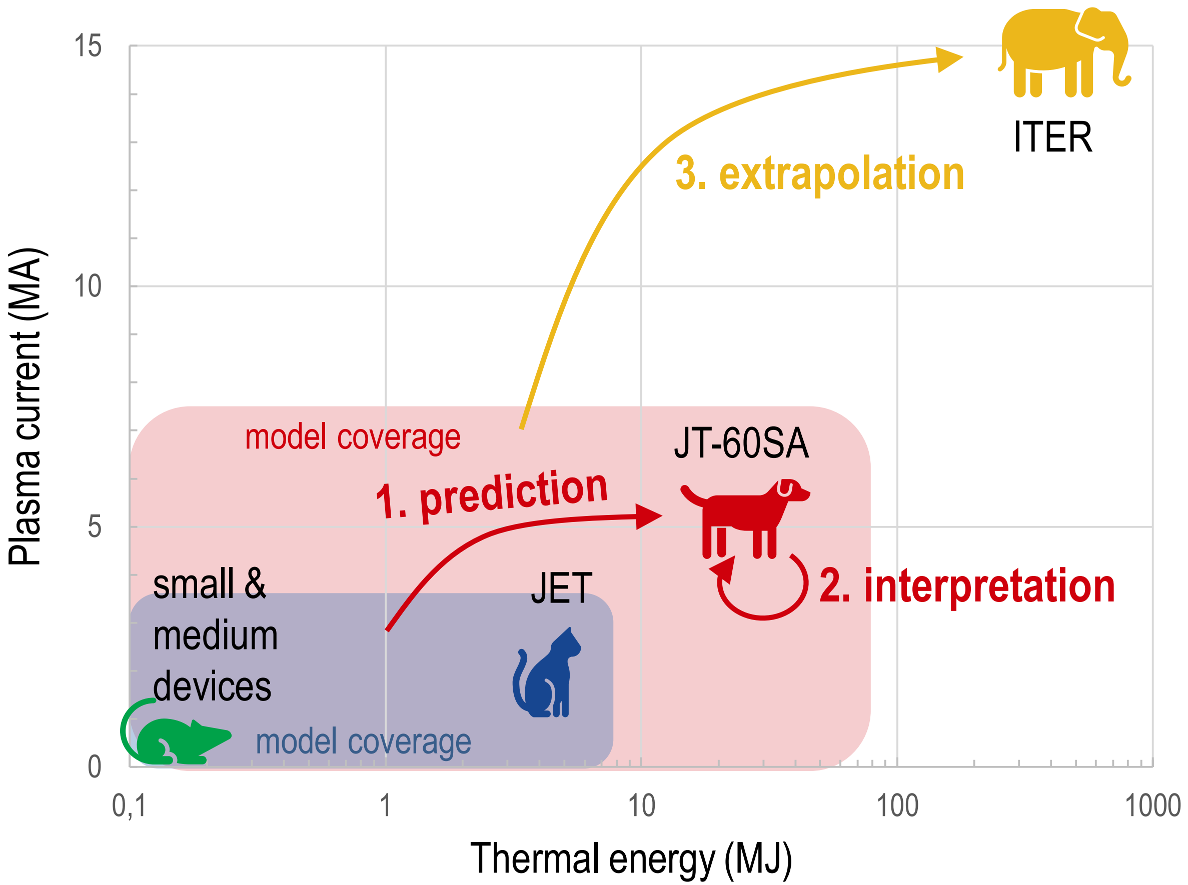
† Dedicated disruption & RE mitigation experiments.

[1] M. Lehnen *et al. J. Nucl. Matter.* **463**, 39 (2015)

Runaway electron modeling for JT-60SA: Plans

Application of transport codes ASTRA-STRAHL[1-3] **for simulations of RE mitigation by MGI**
(background plasma, MGI, RE)

1. Predictive simulations prior to H.I.2. & H.II.3.; prior model validation within TSVV Task 9
   (2022/23† – mid 2023)
2. Interpretive simulations of experiments from H.I.2. and H.II.3.
   (mid 2023 onwards)
3. Model refinement and extrapolation to ITER
   (2024 onwards)



This cartoon is not intended for quantitative statements.

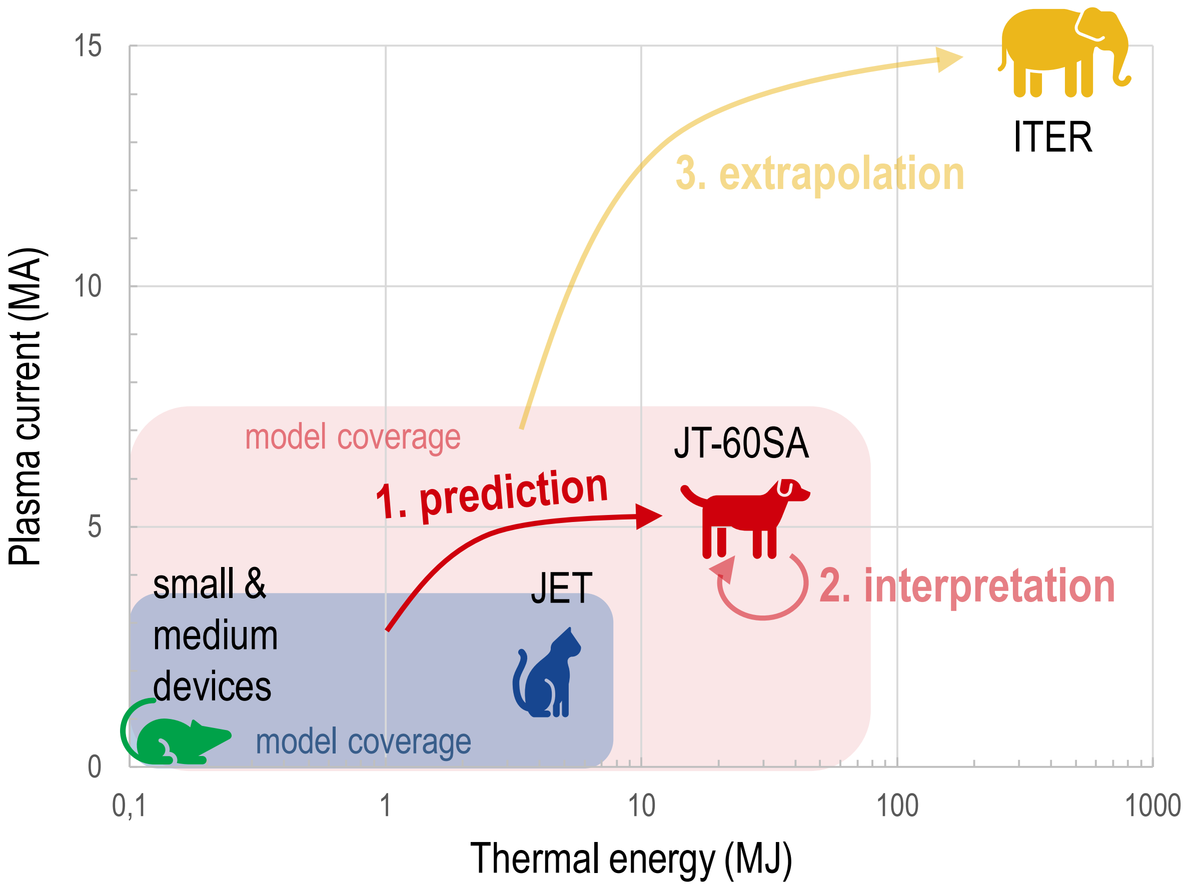
Time line to be updated in due time.
† Depending on MGI deployment.

[1] E. Fable *et al. Plasma Phys. Control. Fusion* **55**, 074007 (2013) [2] R. Dux *et al. Nucl. Fusion* **39**, 1509 (1999) [3] O. Linder *et al. Nucl. Fusion* **60**, 096031 (2020)

Runaway electron modeling for JT-60SA: Plans for predictive simulations

Predictive simulations of JT-60SA prior to operation

- Simulation of JT-60SA "ITER-like" plasmas[1] (e.g. $I_\mathrm{p}/B_\mathrm{t} = 4.6\ \mathrm{MA}/2.28\ \mathrm{T}$)
- Simulations at different I_p, B_t, shape[1]
- Different impurity species (single & mixed injection)
- Impurity amounts



This cartoon is not intended for quantitative statements.

[1] JT-60SA Research Unit. JT-60SA Research Plan (v. 4). (2018)

A note on TSVV Task 9 “Dynamics of REs in Tokamak Disruptions”

Upcoming RE modeling efforts for JT-60SA to benefit from TSVV Task 9 and vice-versa

Organization

- Task leader: Eric Nardon (CEA)
- 1st April 2021 – Dec. 2025
- Group of 13 researchers from 7 institutes
  (CEA, Chalmers University of Technology, EPFL, IPP, Aalto University, CER Budapest)

Plans & goals

- Develop self-consistent, robust and validated models to simulate RE dynamics & mitigation
  - Including ASTRA, CODE, DREAM, ETS, GO, JOREK, LUKE, SOFT
  - Model extensions: RE transport, interactions REs ↔ pellets, beam companion plasma
  - Experimental validation *(synergies with JT-60SA)*
- Find RE avoidance & mitigation methods for ITER
  - Map operational boundaries for ITER DMS
  - Study pre-TQ injection for dilution
  - Study post-CQ injection for RE beam mitigation

ASTRA-STRAHL in a nutshell

Solving macroscopic transport equation

$$\frac{\partial Y}{\partial t} = \left(\frac{\partial V}{\partial \rho}\right)^{-1} \frac{\partial}{\partial \rho}\left(\frac{\partial V}{\partial \rho}\left\langle(\Delta\rho)^2\right\rangle\left\{D\frac{\partial Y}{\partial \rho} - v\,Y\right\}\right) + \sum_j S_j$$

Quantity $Y(t)$	Transport[a] $D(t), v(t)$	Sources S_j
Poloidal magnetic flux $\Psi(t)$		RE current density
Electron temperature $T_e(t)$	MHD induced χ_e^{add}	Impurity radiation
		Equipartition
Ion temperature $T_i(t)$		Equipartition
Electron density $n_e = n_D + \sum_k \langle Z_k \rangle n_k(t)$		
Impurity density $n_{k,i}(t)$	Neoclassical (NEOART)	Rate coefficients (ADAS)
	MHD induced $D^{add}(t), v^{add}(t)$	MGI
RE current density $j_{RE}(t)$		Dreicer, hot-tail, avalanche

ASTRA[1] STRAHL[2] RE source module[3]

[a] Most relevant contributions only.

[1] E. Fable *et al.* *Plasma Phys. Control. Fusion* **55**, 074007 (2013) [2] R. Dux *et al.* *Nucl. Fusion* **39**, 1509 (1999) [3] O. Linder *et al.* *Nucl. Fusion* **60**, 096031 (2020)

ASTRA-STRAHL in a nutshell: The RE source module[1]

Dreicer generation
(momentum space-diffusion)
CODE neural network[2]

avalanche generation
(knock-on collisions)
Analytical expression
considering high-Z effects[3]

hot-tail generation
(rapid cooling)

nuclear generation
(Compton scattering,
tritium decay)
to be included

[1] O. Linder *et al. Nucl. Fusion* **60**, 096031 (2020)

[2] L. Hesslow *et al. J. Plasma Phys.* **85**, 475850601 (2019)

[3] L. Hesslow *et al. Nucl. Fusion* **59**, 084004 (2019)

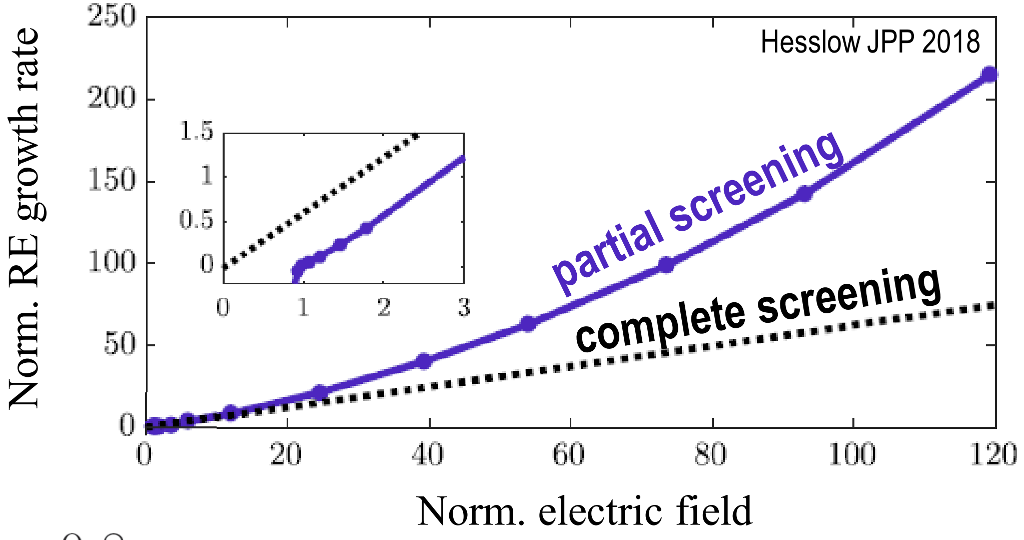
ASTRA-STRAHL in a nutshell: State-of-the-art RE generation models

Importance of high-Z interactions for runaway[1-5]

- Increased impurity friction experience by fast REs; nuclear charge only partially screened by bound electrons ($He^{+} \neq Ar^{+}$)
- Density of target electrons increased

→ Critical electric field for runaway increased

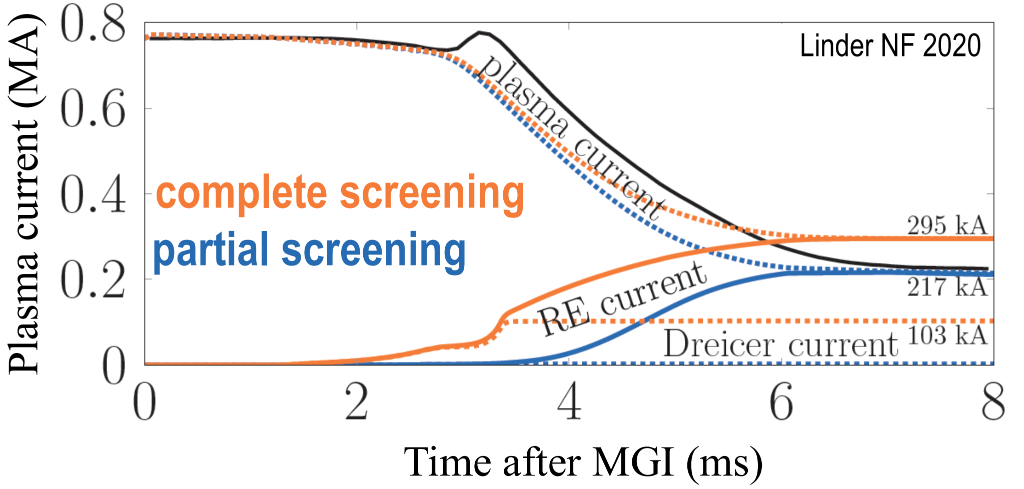
→ Avalanche growth rate increased



Models neglecting these effects[6-7]

- Overestimate Dreicer generation[5,8]
- Underestimate avalanche generation[4,8]

→ **Considering high-Z effects is crucial!**



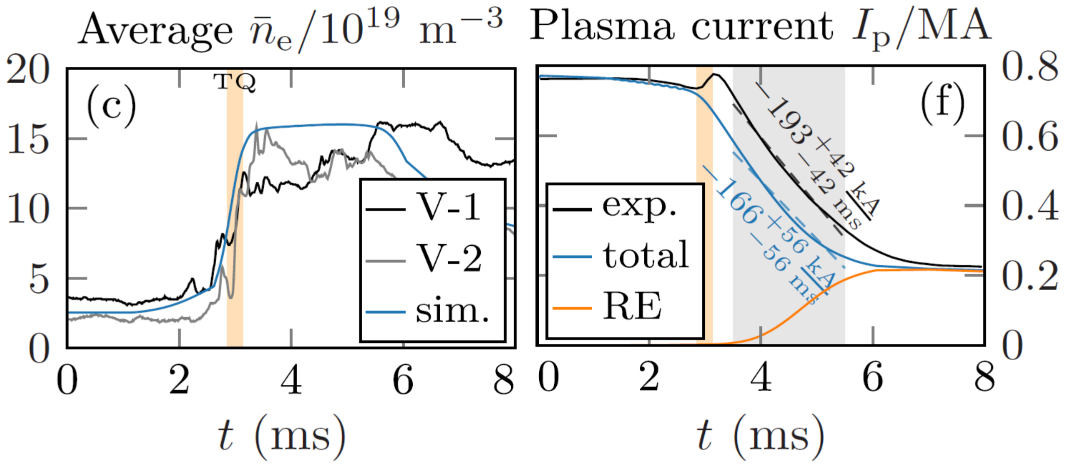
[1] L. Hesslow *et al. Phys. Rev. Lett.* **118**, 255001 (2017)
[2] L. Hesslow *et al. Plasma Phys. Control. Fusion* **60**, 074010 (2018)
[3] L. Hesslow *et al. J. Plasma Phys.* **84**, 905840605 (2018)
[4] L. Hesslow *et al. Nucl. Fusion* **59**, 084004 (2019)
[5] L. Hesslow *et al. J. Plasma Phys.* **85**, 475850601 (2019)
[6] J.W. Connor *et al. Nucl. Fusion* **15**, 415 (1975)
[7] M.N. Rosenbluth *et al. Nucl. Fusion* **37**, 1355 (1997)
[8] O. Linder *et al. Nucl. Fusion* **60**, 096031 (2020)

Example: Application of ASTRA-STRAHL to ASDEX Upgrade

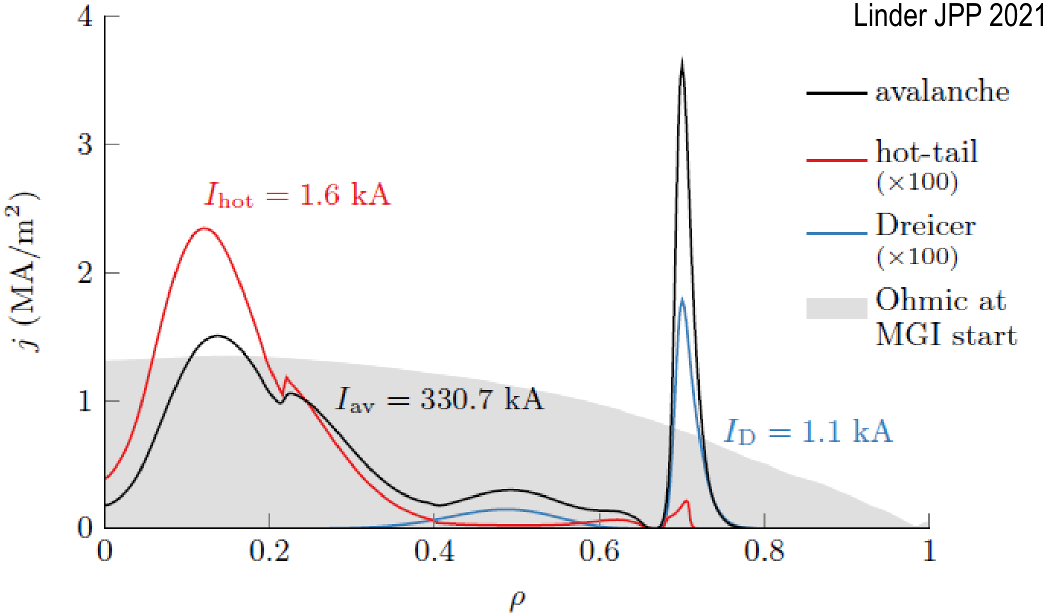
Suitability demonstrated for Ar MGI in ASDEX Upgrade[1,2]

- Key experimental observations reproduced (line averaged n_e, I_p-decay)
- Electron density reproduced → I_{RE} reproduced
- Material propagation through MHD effects and neoclassical effects (non-negligible!)
- State-of-the-art reduced kinetic models for RE generation required (classical analytical formulae inconsistent with experiment; see previous slide)
- RE seed generation similarly due to hot-tail and Dreicer
- Post-disruption RE current avalanche dominated (weakly dependent on RE seed)

Linder NF 2020



Linder JPP 2021

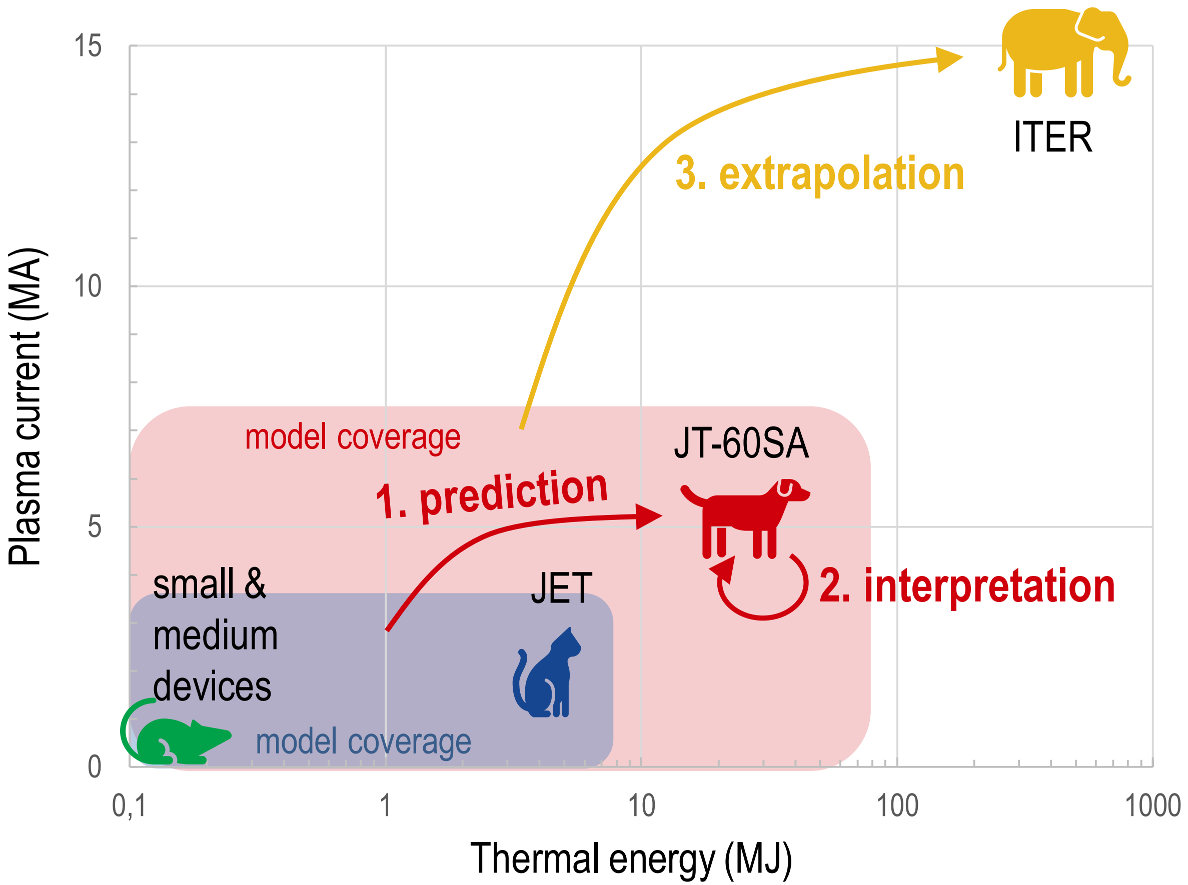


[1] O. Linder *et al. Nucl. Fusion* **60**, 096031 (2020)

[2] O. Linder et al. *J. Plasma Phys.* (submitted). arXiv:2101.04471

Summary

- Simulations of RE generation in JT-60SA using toolkit ASTRA-STRAHL:
    1. prediction
    2. interpretation
    3. extrapolation
- Transport simulations with reduced kinetic RE models
- Tool capabilities demonstrated in AUG; future validation within TSVV Task 9



This cartoon is not intended for quantitative statements.

Appendix

Further reading: ASTRA-STRAHL for simulations of RE generation

IPP

More details on applications of ASTRA-STRAHL in self-consistent simulations of background plasma, MGI and REs following Ar MGI in ASDEX Upgrade #33108 are presented in the following publications:

IAEA **nuclear fusion**

PAPER

Self-consistent modeling of runaway electron generation in massive gas injection scenarios in ASDEX Upgrade

O. Linder[1], E. Fable[1], F. Jenko[1], G. Papp[1], G. Pautasso[1], the ASDEX Upgrade team[2,1] and the EUROfusion MST1 team[3,1]

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Citation O. Linder *et al* 2020 *Nucl. Fusion* **60** 096031

Article PDF

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arXiv.org > physics > arXiv:2101.04471

Physics > Plasma Physics

[Submitted on 12 Jan 2021 (v1), last revised 13 Jan 2021 (this version, v2)]

Electron runaway in ASDEX Upgrade experiments of varying core temperature

O. Linder (1), G. Papp (1), E. Fable (1), F. Jenko (1), G. Pautasso (1), the ASDEX Upgrade Team, the EUROfusion MST1 Team ((1) Max-Planck-Institut für Plasmaphysik, Garching, Germany)

Comments: 23 pages, 9 figures; submitted to the Journal of Plasma Physics

Subjects: **Plasma Physics (physics.plasm-ph)**

Cite as: arXiv:2101.04471 **[physics.plasm-ph]**

(or arXiv:2101.04471v2 **[physics.plasm-ph]** for this version)

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https://arxiv.org/abs/2101.04471

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4.3,7.3,8.1,9.8,10.1 O. Linder, E. Fable, F. Jenko *et al*. Self-consistent modeling of runaway electron generation in massive gas injection scenarios in ASDEX Upgrade. *Nucl. Fusion* **60**, 096031 (2020)

8.2,9.5 L. Hesslow, L. Unnerfelt, O. Vallhagen *et al*. Evaluation of the Dreicerrunaway growth rate in the presence of high-Z impurities using a neural network. *J. Plasma Phys.* **85**, 475850601 (2019)

8.3,9.4 L. Hesslow, O. Embreus, O. Vallhagen *et al*. Influence of massive material injection on avalanche runaway generation during tokamak disruptions. *Nucl. Fusion* **59**, 084004 (2019)

9.1 L. Hesslow, O. Embreus, A. Stahl *et al*. Effect of Partially Screened Nuclei on Fast-Electron Dynamics. *Phys. Rev. Lett.* **118**, 255001 (2017)

9.2 L. Hesslow, O. Embreus, G.J. Wilkie *et al*. Effect of partially ionized impurities and radiation on the effective critical electric field for runaway generation. *Plasma Phys. Control. Fusion* **60**, 074010 (2018)

9.3 L. Hesslow, O. Embreus, M. Hoppe *et al*. Generalized collision operator for fast electrons interacting with partially ionized impurities. *J. Plasma Phys.* **84**, 905840605 (2018)

9.6 J.W. Connor and R.J. Hastie. Relativistic limitations on runaway electrons. *Nucl. Fusion* **15**, 415 (1975)

9.7 M.N. Rosenbluth and S.V. Putvinski. Theory for avalanche of runaway electrons in tokamaks. *Nucl. Fusion* **37**, 1355 (1997)

10.2 O. Linder, G. Papp, E. Fable *et al*. Electron runaway in ASDEX Upgrade experiments of varying core temperature. *Submitted to J. Plasma Phys.* arXiv:2101.04471 (2021)